Internal Kinematics of Microstructures and Implications

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Abstract. High resolution images at different wavelengths show the common presence of structures and microstructures in planetary nebulae (PNe), which are not well incorporated to the existing models for the formation of these objects. We summarize how studies of the internal kinematics, combined with the information provided by high resolution images, may help to establish the nature and possible origin of the observed structures as well as to provide information about the physical processes involved in the formation and evolution of PNe.

1. Introduction

Even though planetary nebulae (PNe) have been extensively observed, the processes involved in their formation continue being matter of debate. The lack of spherical symmetry in most PNe (e.g., Sahai & Trauger 1998) and the existence of jets in PNe (e.g., Guerrero et al. 2002) have contributed to the development of novel scenarios and models which provide different explanations for the main characteristics of PNe (see Balick & Frank 2002 for a recent review). However, high resolution images show the common presence of structures and microstructures at subarcsecond scales, like multiple bipolar lobes, disks, knots, arcs (e.g., Sahai & Trauger 1998; O'Dell et al. 2002), which need to be explained and incorporated to the models. Hence, it is necessary to obtain a "complete" information about the observed structures. In this respect, (high resolution) spectroscopic observations allow us to obtain the internal kinematics of the structures and represent an ideal complement to the information provided by the direct images.

In this paper we illustrate the capabilities of the kinematic analysis to infer the nature of the observed structures and which role they may play in the formation of PNe. Particular attention will be drawn to the identification of jets and binary central stars from a kinematical analysis, and to the spatio-kinematic properties of the microstructures recently observed in water maser emission.

2. Identification of Jets in PNe

In addition to the PNe with jets already identified, high resolution images show that many more PNe contain structures which could be collimated outflows (Sahai & Trauger 1998). Nevertheless, it has been demonstrated that some jet-like features observed in direct images are not related to collimated outflows (Goncalvez et al. 2002). In order to establish the jet nature of a particular

feature, analysis of its kinematical properties is necessary. A jet should present (1) a relatively high radial velocity, as compared with the radial velocities observed in the rest of the nebula, (2) a narrow velocity width, indicating high collimation or, alternatively, a very large velocity width indicating bow-shock excitation (Solf 1994), and, in general, (3) the strong [NII] emission typical of jets in PNe. It should be noted that the radial velocity depends on the direction of the jet with respect to the observer, so that a low radial velocity does not necessarily excludes a jet nature. This is the case of the jet-like features observed in HST images of He 2-90 (Sahai & Nyman 2000), which were confirmed through high resolution spectroscopy to be true jets in spite of their relatively low radial velocity ($\simeq 26$ km s^{-1}, Guerrero et al. 2001) which is due to a simple projection effect (Sahai et al. 2002).

Spectroscopy is crucial to identify jets which cannot be observed in direct images because of their relatively faintness weak emission and projection effects. This is the case of NGC 2392, the first PN in which jets have been detected (Gieseking, Becker & Solf 1985). The jets in NGC 2392 can be easily identified in long-slit spectra, at the appropriate position angles of the slit, as high-velocity ($\simeq 190$ km s^{-1}), narrow ($\simeq 8$ km s^{-1}) and elongated bipolar emission features.
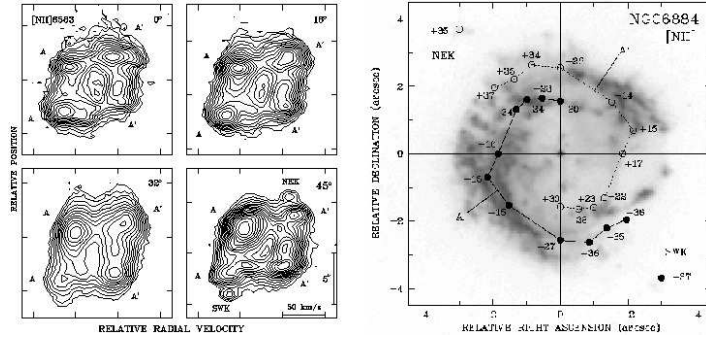

Figure 1.   (*left*) Position-velocity contour maps deduced from high resolution long-slit spectra of the [NII] emission line from NGC 6884 at four different PAs (indicated at the upper right corner). Kinematic components (A, A', NEK and SWK) are indicated. (*right*) Grey-scale representation of a [NII] image of NGC 6884 obtained with the HST. Filled (open) circles mark the positions of the blueshifted (redshifted) kinematic components as deduced from a set of seven long-slit spectra. The numbers are radial velocities (km s^{-1}) with respect to the systemic velocity. (0,0) marks the position of the central star.

In other PNe, structures observed in direct images can only be identified as jets with the aid of high resolution spectroscopy. An interesting case is NGC 6884. Figure 1 presents an [NII] image, long-slit spectra and the results obtained in NGC 6884 (Miranda, Guerrero & Torrelles 1999). The [NII] image shows a bright knotty structure with a very peculiar shape. The analysis of the kinematics shows that this structure is the projection of two narrow spirals with a high point-symmetry in space and radial velocity. The observed properties allow us to interpret the spirals as a precessing bipolar jet. Moreover, from a simple spatio-kinematic model, estimates for the jet velocity ($\simeq 55$ km s^{-1}),

precession angle ($\simeq 120°$) and precession period ($\simeq 500 \times [\text{D(kpc)}/2]$ yr can be deduced.

3.   Jet kinematics and binary central stars

Binary stars are invoked in many scenarios of PN formation. Although the fraction of binaries among PN central stars is noticeably increasing (Pollaco 2004), direct detection may be difficult due to the nature, characteristics or the own evolution of the binary (e.g., Soker 1996). Binary evolution may have an impact in the nebular properties, which should be different from that of a single star. Thus, several methods have been developed in order to infer the possible presence of a binary central star through detailed analysis of the nebula. Soker (1994) and Soker, Rappaport & Harpaz (1998) analyze the position of the central star with respect to the nebular center, as deduced from direct imaging. According to this method, the presence of a binary central star may be inferred from its off-centered location in the nebula, being possible to distinguish between wide and close binaries.

On the basis of high resolution spectroscopy, Miranda et al. (2001a) propose that a difference between the systemic velocity of a bipolar jet and that of the main nebular shell may be the signature of orbital motion, this difference being a lower limit to the orbital velocity (see Miranda 2002 for details). Systemic velocity differences of $\simeq 10$ km s^{-1} have been found in Hu 2-1 and IC 4846, two PNe with bipolar jets, which would imply an orbital separation ≤ 30 AU and a period ≤ 100 yr (Miranda 2001a,b). These orbital parameters suggest interacting binaries at the center of Hu 2-1 and IC 4846. Systemic velocity differences as low as $\simeq 2$ km s^{-1} may be detected with a spectral resolution higher than $\simeq 12$ km s^{-1}. Therefore, this method may be sensitive to binary central stars with separations up to a few tens AU.

4.   Microstructures in Water Maser Emission

Water maser emission, typical of AGB stars (e.g., Habing 1996), persists in the post-AGB, proto-PN and can be detected in extremely young PNe (e.g., Likkel & Morris 1988; Marvel & Boboltz 1999; Miranda et al. 2001c). High resolution (VLA or VLBA) observations of water masers in these objects are producing exciting results with important implications for our understanding of PN formation. In the AGB or post-AGB star W43A, the water masers trace an extremely young, precessing bipolar jet moving at $\simeq 150$ km s^{-1} (Imai et al. 2002). In the proto-PN IRAS 16342-3814, the water maser emission arises at the tips of the bipolar lobes, probably associated with a bow-shock, moving at ≥ 160 km s^{-1} (Morris et al. 2003; Claussen 2004).

The first PN in which water maser emission was detected, is K 3-35 (Miranda et al. 2001c). Recently, de Gregorio et al. (2004) have carried out a survey for water masers in a sample of 27 PNe and detection was obtained in IRAS 17347-3139. Moreover, de Gregorio et al. (2004) deduce a $T_{eff} \geq 26000$ K from the radio continuum emission for the central star of IRAS 17347-3139, indicating an extremely young PN. In the following we describe the results obtained in these two PNe.
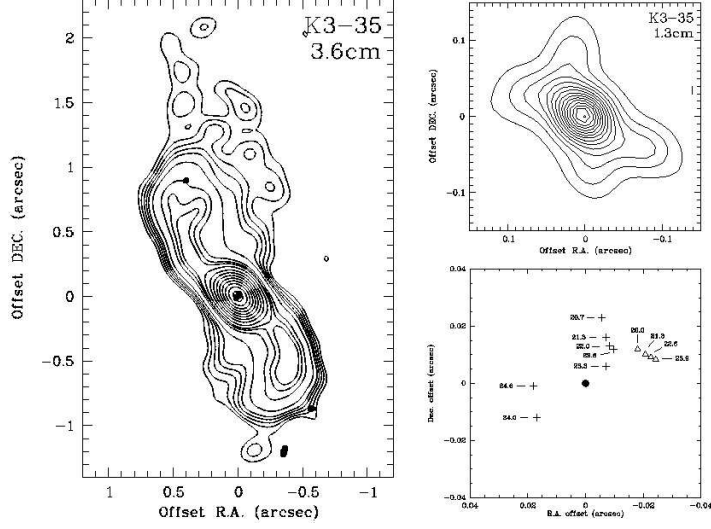
Figure 2.   (*left*) Contours of the 3.6 cm continuum emission from K 3-35. Black dots represent the four regions where water maser emission has been detected. (*upper right*) Contours of the 1.3 cm continuum emission. (*bottom right*) Position of the water maser spots at the center of the nebula as observed in 1999 September (crosses) and in 2002 May (triangles). The numbers are LSR radial velocities (km s^{-1}). The black dot at the center marks the position of the 1.3 cm continuum emission peak.

K 3-35 is a bipolar PN containing a bipolar jet and an extended equatorial disk (Aaquist & Kwok 1989; Aaquist 1993; Miranda et al. 1998, 2000). Figure 2 shows VLA radio continuum maps of K 3-35 at 3.6 cm and 1.3 cm, and the location of the water masers. Water maser emission is detected at a radius of $\simeq 85$ AU (for a distance of 5 kpc) from the center of the object and at the tips of the bipolar jet, at $\simeq 5000$ AU from the center (Miranda et al. 2001c).

The water masers at radius $\simeq 85$ AU probably trace the innermost regions of the extended equatorial disk. The disk is magnetized as indicated by the strong polarization of the OH maser emission from the disk (Miranda et al. 2001c). Changes in $\simeq 2.5$ yr in the positions of the water maser spots in the disk have been observed (see Fig. 2; de Gregorio et al. 2004). Closely spaced multi-epochs observations are now necessary to discriminate whether the observed changes are due to proper motions or to a process of destruction/creation of water maser shells associated to an ionization/shock front.

The existence of the distant water masers in K 3-35 is puzzling. Because the the nebula is ionized, Miranda et al. (2001c) invoke a shielding mechanism that prevents the distant water molecules to be destroyed by the stellar radiation. Given that K 3-35 is extremely young, shielding could be provided by large amounts of neutral material in the nebula. In addition, the physical conditions required to pump the water maser (Marvel 1997) are not expected to exist at such enormous distances from the central star. The bipolar jet in K 3-35 has been proposed to be the agent responsible for the excitation of the distant water
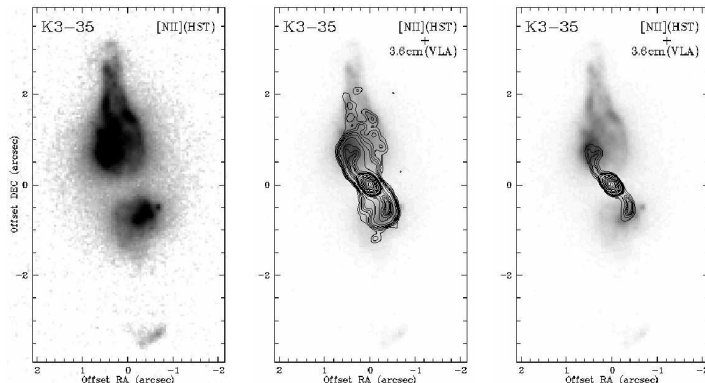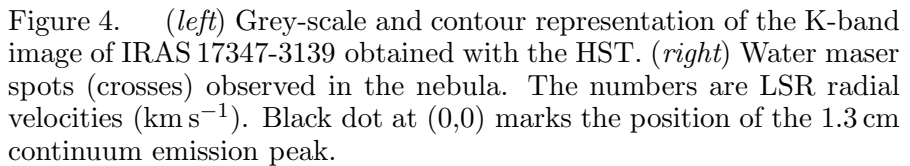
Figure 3.   Grey-scale maps of the [NII] image of K 3-35 obtained with the HST. In the middle and right panels two sets of contours have been superimposed which represent the 3.6 cm continuum emission from the nebula.

masers, given their spatio-kinematical association (Miranda et al. 2001c). This conclusion is reinforced by comparing the 3.6 cm continuum map with a HST [NII] image of K 3-35 obtained recently by R. Sahai, which is shown in Figure 3. The image shows a bipolar PNe with two lobes separated by a prominent dark lane (corresponding to the equatorial disk) and surrounded by a faint elliptical envelope. The previously detected bipolar knots (Miranda et al. 1998) dominate the emission from the lobes. The radio jet is clearly associated with these bright knots which may be related to a jet-envelope interaction. If so, the distant water masers could arise in still neutral clumps which are compressed and heated through this interaction.

Figure 4 shows the HST K-band image of IRAS 17347-3139 (Bobrowsky, Greeley & Meixner 1999) and the results of the VLA water maser observations (de Gregorio et al. 2004). The image shows a bipolar nebula with the main axis at PA $\simeq -40°$. The detected water maser spots trace an ellipse of $\simeq 0''2 \times 0''1$ in size with the major axis oriented almost perpendicular to the main nebular axis. The observed morphology suggests that the water masers trace an equatorial disk. The kinematics of the water masers indicates that both rotating and expanding motions are present in the disk (de Gregorio et al. 2004).

The number of proto-PNe and PNe with water maser emission that have been observed at high resolution, is still scarce, so that general conclusions cannot be drawn. Nevertheless, it is interesting that jets are common to the few objects observed, Moreover, these jets operate well before the star enters its PN phase. Equatorial disks are also found in these objects (see references above). Remarkably, clear differences are observed in the kinematics of these disks. Expanding motions dominate in the disk of K 3-35, as it is observed in more evolved PNe. The kinematics of the disk in IRAS 17347-3139 is intermediate to that of the rotating disk detected in the proto-PN Red Rectangle (Bujarrabal et al. 2003) and that of expanding disks in PNe. We speculate that differences in disk kinematics could be related to the evolutionary status of the object. We note that T_{eff} for the central star of K 3-35 is ≥ 60000 K (Miranda et al. 2000)

Figure 4.   (*left*) Grey-scale and contour representation of the K-band image of IRAS 17347-3139 obtained with the HST. (*right*) Water maser spots (crosses) observed in the nebula. The numbers are LSR radial velocities (km s^{-1}). Black dot at (0,0) marks the position of the 1.3 cm continuum emission peak.

whereas it is lower ($\simeq$ 26000 K) for the central star of IRAS 17347-3139. This suggests that IRAS 17347-3139 may represent an earlier stage in PN evolution than K 3-35. It is possible that the fast wind in IRAS 17347-3139 is not yet energetic enough to swept up material in the dense equatorial plane and the disk preserves part of its original (rotating) motions before becoming a purely expanding disk typical of PNe.

5.   Conclusions

Studies of the internal kinematics provide crucial information on the nature of the structures and microstructures present in PNe and the processes involved in the formation of these objects. The collimated outflow nature of jet-like features observed in direct images can be established by analyzing the kinematical properties of these features. Information about possible binary central stars can also be obtained from the internal kinematics of PNe with bipolar jets. Microstructures are also observed in recent observations of water maser emission, at high spatial and spectral resolution, in post-AGB stars, proto-PNe and extremely young PNe. These microstructures represent disks or jets or are associated with collimated outflows. These observations provide support to the idea that jets are a basic ingredient in the formation and evolution of some PNe and that they may be operating much before the star becomes a PN. The kinematics of the disks is varied and rotating and expanding motions can be observed as well as a combination of both. The kinematics of the disks could be related to the evolutionary stage of the object.

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